Predictability, Effort and (Anti-)Resonance in Complex Object Control

Pauline Maurice, Neville Hogan, Dagmar Sternad

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I. INTRODUCTION

Manipulation of complex objects as in tool use is ubiquitous in everyday life and has given humans an evolutionary advantage. Yet there has been little research on complex interactive skills and control principles for such actions remain elusive. To gain insight into the control of complex objects, the present study examined the strategies that humans choose when rhythmically manipulating an object with internal dynamics, such as carrying a cup of coffee. The dynamics of the object can render the temporal evolution of the system complex, possibly even chaotic, and hence difficult to predict.

II. METHOD

A cart-and-pendulum model mimicking coffee sloshing in a cup was implemented in a virtual environment with a haptic interface. Ten participants rhythmically manipulated a virtual cup containing a ball; they were free to choose the frequency of oscillation, while the amplitude was imposed. To evaluate the strategies that humans adopted we mathematically examined the cart-and-pendulum system coupled to a model of hand impedance (Fig 1). The equations of motion of the model are

$$\begin{aligned}
&(m_c + m_p)\ddot{X} = m_p d\left(\dot{\theta}^2 sin\theta - \ddot{\theta} cos\theta\right) + F_{inter} \\
&\ddot{\theta} = -\frac{\ddot{X}}{d} cos\theta - \frac{g}{d} sin\theta \\
&F_{inter} = F_{input} - K\left(X - X^{des}\right) - B\left(\dot{X} - \dot{X}^{des}\right)
\end{aligned} \tag{1}$$

with X the cart position and m_c its mass, θ the pendulum angle, m_p its mass and d its length, K and B the hand stiffness and damping, F_{inter} the interaction force between the cart and the human hand, and F_{input} the force required to follow a desired trajectory $(X^{des}, \dot{X}^{des})$. This task-based approach allowed us to evaluate alternative execution strategies, *i.e.* different values of frequency and hand impedance that could be used to perform the task.

This study examined two hypotheses: 1) humans increase predictability of the object dynamics, measured by the mutual information between the interaction force and the object dynamics, 2) humans decrease interaction forces between hand and object. Predictability of the object dynamics was characterized by the mutual information between the input and the output of the system, *i.e.* the cart trajectory $\phi(t) = arctan\left(\dot{X}/(2\pi f X)\right)$ and the interaction force F_{inter}

$$MI(\phi, F_{inter}) = \iint p\left(\phi, F_{inter}\right) ln\left[\frac{p\left(\phi, F_{inter}\right)}{p\left(\phi\right)\, p\left(F_{inter}\right)}\right] d\phi\, dF_{inter}$$

The force required to perform the task was estimated by the root mean square of the continuous interaction force

$$RMSF(F_{inter}) = \frac{1}{T}\int_0^T F_{inter}^2(t)\, dt$$

where T is the duration of the task.

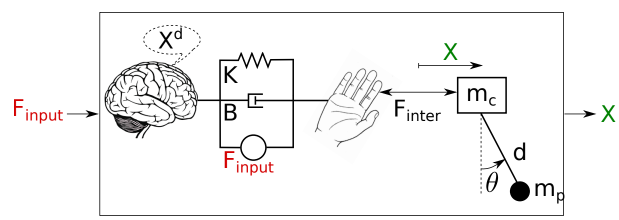

Fig. 1. Model used to analyze the dynamics of the task in simulation: Forward dynamics of the cart-and-pendulum system coupled to a model of hand impedance.

III. RESULTS

First analysis revealed that humans chose one of two distinct strategies, either with low or high frequency, respectively. Mathematical analyses revealed that both strategies adopted by participants generated highly predictable behavior, but did not reduce interaction forces. Fig 2 shows a 2D contour map of the result variables, plotted for a constant value of hand damping $B = 10 N.s/m$. The result space for MI contains one area of very low predictability for frequencies around 0.8 Hz. This area coincides with an area where the interaction force is low; therefore the two hypotheses are exclusive. Reciprocally, for frequencies around 0.64 Hz and higher that 1.20 Hz, predictability is

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high, but interaction force is high as well. Participants' strategies are largely clustered in the pink areas, consistent with Hypothesis 1. The same set of points plotted in panel B did not lie in the green areas, counter to Hypothesis 2.

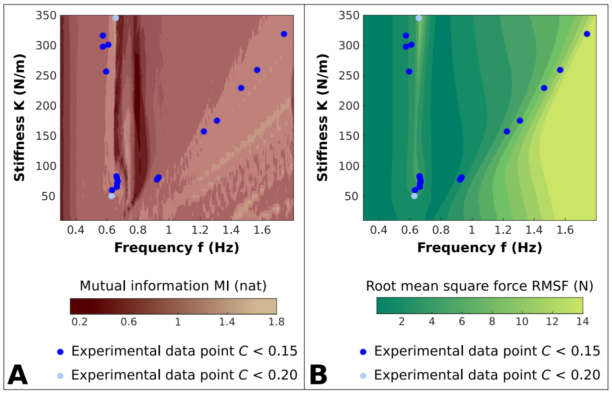

Fig. 2. 2D maps of the mutual information MI between the cart trajectory and interaction force (A) and of the root mean squared interaction force RMSF (B) in the result space spanned by two of the execution variables: f and K. The hand damping B was fixed at $10N.s/m$. The blue dots represent the strategies (f, K) adopted by participants in the behavioral experiment. The trials represented are those where the hand damping was $8 < B < 12N.s/m$. The darker dots correspond to trials for which the impedance fit was good; the lighter dots are trials where the impedance fit is not very good.

IV. CONCLUSION

These results demonstrate that in complex object manipulation, humans do not prioritize effort, but rather seek strategies where interactions are predictable. In addition, predictability was found to be closely related to the resonance and anti-resonance structure of the system. This finding highlights that physical interactions with complex objects, present in numerous daily activities, introduce new challenges and engage different control principles than identified in the manipulation of rigid objects or in unconstrained movements.

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